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Potential of Wind-Powered Renewable Energy Membrane Systems for Ghana

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Abstract: Areas of the world that lack fresh water often have an ample supply of wind or solar energy, making renewable energy an attractive option as a power source for desalination systems. Particularly, wind energy is attractive because of its relatively low cost, high efficiency, and recent technological advancements in this area of research. To open system applicability to a broader range of geographical areas, the feasibility of substituting solar panels with a wind turbine on an existing membrane desalination system that has undergone testing in the Australian outback is examined. The use of wind turbines will provide greater scope for the system's implementation in various parts of the world according to the local wind or solar resources. A comparison of several small wind turbines coupled with wind speed data from Ghana showed that a 1kW FuturEnergy wind turbine would give the best performance for the lowest cost and is therefore the most appropriate for coupling with the membrane system. The predicted permeate flowrate is 1.3 m³/day at a specific energy consumption (SEC) of 1.8 kWh/m³.

Keywords: Brackish water; Ghana; Membranes; Reverse osmosis; Wind power

Introduction

As a result of the worldwide water crisis, the United Nations declared the years 2005 to 2015 the International Decade for Action 'Water for Life' [1]. The primary goal of this effort is to fulfil the international commitments regarding water and related issues by 2015. This includes the Millennium Development Goals (MDG) which are to reduce by half the proportion of people with sustainable access to safe drinking water and stop the unsustainable exploitation of water resources [2]. A survey by the World Health Organization and UNICEF in 2002 showed that the MDG for safe drinking water should be achieved in most areas of the world with the exception of sub-Saharan Africa [3]. The fact that an estimated 42,000 people die every week from diseases related to unsafe drinking water and inadequate sanitation means that there is a need for an economical means of purifying the available water sources in order to prevent the spread of water-borne diseases.

The use of renewable energy driven reverse osmosis (RO) membrane filtration systems can be a viable alternative to other methods of filtration, especially for remote communities with poor potable water and energy supplies. The fact that renewable energy sources generate an intermittent supply of power creates many challenges when trying to match them to the water requirements of a small community. The use of wind power is particularly attractive because of the relative maturity of the technology associated with this resource and the fact that it allows greater flexibility of the existing solar powered system. The existing renewable energy membrane system is designed to desalinate water from brackish sources and has undergone testing in the Australian outback [4, 5]. The use of wind turbines will provide greater flexibility for implementing the RO membrane system in various locations around the world.

There have been several studies performed on the use of wind turbines to power membrane filtration units ranging from small (<10 m³/day) [6-12] to large-scale (>100 m³/day) [13, 14]. Most of them are either mechanically driven systems using multi-vaned windmills or electrically driven systems using small scale wind turbines. Both systems require the output from the wind turbine to drive a pump in order to raise the pressure of the feed water so that it can pass through a membrane filtration system. The required pressure of the feedwater is linked closely to the performance of the system and the quality of the feed water. *Table 1* demonstrates how RO systems designed for seawater desalination (35 g/L) require an operating pressure of up to ten times that of systems designed for brackish water desalination (1-10 g/L). This paper deals with the implementation of small scale wind-powered systems, examples of which are shown in *Table 1*.

One of the most important criteria for determining the feasibility of these systems is the specific energy consumption (SEC, unit: kWh/m³), as this ultimately determines the cost of the system. This is due to the fact that the SEC demonstrates the water productivity and power consumption, which translates into the required wind turbine output and membrane surface area and hence capital investment. Recovery describes the amount of clean water (permeate) that is produced compared to the feed flow. In the case of brackish desalination systems, low recoveries (10-25%) are sometimes used to reduce fouling of the RO membrane and to avoid the generation of a highly concentrated waste brine. This means that four to ten times as much feed water compared to permeate must be pumped through the system for any given output, although this water may be suitable for non-potable purposes in the case of brackish water applications [15].

Table 1. Overview of small scale wind-powered membrane filtration units (brackish and seawater).

Location	TDS (g/L)	Pressure (bar)	Salt Retention (%)	Recovery (%)	Permeate (m³/d)	Wind Turbine (kW)	Energy Storage	SEC (kWh/m³)	Ref.
UK	40	40-60	97*	30-45†	8.5†	2.2	None	3.4†	[6]
Germany	36	80	—	27*	6	6	Battery	11	[12]
Colombia	35	3.4-5.5	99	3.0-9.7	0.4	0.9	None	—	[11]
Hawaii	3	5.2-7.2	97	20	4	(Multi-vaned)	Pressure stabilizer	1.1*	[10]
Australia	2-6	6-11	83	9.3	0.21	~ 0.15 (Multi-vaned)	Pressure vessel	0.7*	[9]
Greece	36	58	99*	15	0.6-1	0.9 (hybrid)	Battery bank	16.9*	[8]

*Calculated by current authors †Simulated results

A variable flow RO seawater desalination unit (UK) powered by a 2.2 kW wind turbine underwent preliminary testing at the Centre for Renewable Energy Systems Technology (CREST) at Loughborough University [6, 15]. The system had no battery storage, so that the instantaneous wind speed had a direct effect on the fresh water production. The pumping system used a medium and a high-pressure pump in order to maximise the use of the wind energy and control the flow of water. In addition, a Clark pump was used to recover energy from the concentrate stream (annual average energy efficiency of 93%), thereby increasing the overall energy efficiency [17]. However, the Clark pump was only tested at the high pressures required for seawater desalination (40-60 bar), so further testing at low pressures would be required to determine its feasibility for brackish water desalination. Preliminary experimental results showed that if the permeate flow was discontinued for any great length of time (not formally assessed), the pressure would drop considerably when the system was restarted and the permeate concentration would overshoot to high values before returning to normal. This was attributed to natural osmosis occurring at levels below the osmotic pressure and indicates the importance of keeping adequate pressure or flowrate in order to the feed water flowing to avoid spikes in permeate concentration [15]. It is also important to have an adequate electronic control mechanism in order to reduce the likelihood of surges in pressure and flow and therefore avoid damage to the RO membrane. The net present value of the system was calculated to be £51,000 with an estimated cost of water of 0.80£/m³ based on a system lifetime of 20 years.

An example of a multi-vaned windmill driven design is the prototype system on Coconut Island off the coast of Hawaii, where the windmill is used to mechanically drive a pump in order to raise the pressure of the feedwater for RO desalination [10]. A feedback control mechanism was developed that enabled the system to be operated satisfactorily under mild ambient wind speeds of 5 m/s or less. A flow/pressure stabilizer was used in order to regulate the pressure and flowrate to the RO system thereby increasing the system efficiency. The RO system could process 13 L/min of brackish water with an average rejection rate of 97% and recovery ratio of 20%. This study showed that in general, the energy efficiency of the system decreased as the wind speed increased. The system was found to have an average energy efficiency of 35%.

A rotary-vane windmill was also used as the power source for a RO desalination unit in Australia [9]. The low-pressure system was designed for brackish water desalination and tested over a period of 13 months. The system freshwater production was 150-300 L/d at an average wind speed of 3 m/s. Recovery ranged from 6.2-11.9% whilst the salt rejection averaged 83%. The system included a pressure vessel to store feedwater under pressure to keep flow and pressure at an acceptable rate, and a small diesel or portable gasoline pump was used during periods of low energy input and high demand. It was found that below wind speeds of 4.5 m/s, the system relied on the stored energy in the pressure vessel. A cost comparison showed that wind-powered RO is economically viable in comparison to similar technologies at production rates of 500 L/d or more. However, a cost analysis showed that it was still more economical to cart water around 30-40 km than to desalinate using RO technologies and pumping using diesel equipment.

With all of the systems studied, the actual cost of fresh water due to the life cycle cost (cost of the system over its entire life span; generally taken as 20 years) of the RO system becomes one of the most important factors influencing its wide scale implementation. An economic analysis of wind-powered desalination showed that the main factors influencing the cost of fresh water for a wind-powered RO plan are plant capacity, specific energy consumption, operation and maintenance of the RO plant, average wind speed and the real discount rate (the difference between the cost of water for a wind-powered RO plant and a conventional energy driven one) [13]. A cost analysis of a RO desalination unit powered by wind turbines and photovoltaics using a theoretical model showed that the PV system has the highest proportion of the annual system cost (27%), due to its high capital cost [8]. The study also showed that it is much more cost-effective to store fresh water as opposed to electrical energy, demonstrated by the cost of storing water in a tank (1%) compared to electrical energy storage in batteries (12%). The health implications associated with storing fresh water are an issue that must be taken into consideration in designing these systems combined with the advantage of increased security of water availability due to water storage.

For wind powered desalination, wind speed has a direct effect on the running cost of a system, as it determines system productivity. An analytical study on using wind power (>50kW) for reverse osmosis desalination plants looked at their design by determining the optimum plant size with respect to the membrane, and the type of turbine according to the energy required and the site characteristics [14]. The results indicated that the unit cost of water produced by desalination can be reduced by up to 20% for regions with a mean wind velocity higher than 5 m/s.

Reverse Osmosis Membrane System

The objective of this study is to look at the feasibility of replacing the solar panels on an existing membrane desalination system with a wind turbine. The use of wind turbines could provide increased performance and significant cost savings for system implementation in areas with a good wind resource. All of the components for the system are mounted on an off-road trailer to allow easier access to remote areas. The system is designed to supply up to 1000 L of fresh water per day from brackish groundwater sources, which is sufficient for a small community. The power requirements of the system are met by four $24V_{DC}$ photovoltaic modules that each provide a maximum power output of 150 W [4]. The main power requirement for the membrane system is a 300 W progressive cavity pump that draws the feed water through an ultrafiltration stage (at -0.5 bar) before pumping it through the reverse osmosis stage (up to 12 bar). The ultrafiltration stage consists of six Zenon ZW10 membranes connected in parallel that are immersed in a 300 L stainless steel tank. The purpose of these ultrafiltration membranes is to remove particles, viruses and bacteria as well as act as a pre-treatment stage to reduce fouling of the reverse osmosis membrane, which removes the salt and trace contaminants.

The system is designed to operate without storing energy in batteries, as they are expensive and generally cause most faults in power supplies in remote areas [18]. In higher temperatures, the batteries degrade more quickly and can last for as little as two years, which increases the running costs of the system and requires additional maintenance. In addition, losses of up to 20% can occur when the current is directed into and out of the battery. A maximum-power-point tracker (MPPT) is essential for efficient operation of the pump when it is directly connected to the PV modules [18]. This device operates by trading voltage for current, so that at low light levels, more current can be provided to the pump. The voltage remains very constant due to the MPPT, so the operating pressure of the system is directly proportional to the current drawn from the solar panels [19]. The fact that this system operates without energy storage means that wind fluctuations may have a direct effect on the quantity and quality of fresh water produced, and some kind of equivalent MPPT may need to be designed. The sizing of the wind turbine is important in order to operate within the design window of the membrane system (in terms of flow, pressure, crossflow velocity, pressure and flux) as large fluctuations in the pressure and flow may cause membrane damage [5].

In order to perform a wind turbine comparison and predict the performance of the system in a realistic environment, a study is performed on its implementation potential in Ghana. This West African country was chosen as links have been made with Kwame Nkrumah University of Science and Technology and water samples have been taken from various boreholes and wells across the country. A recent study showed that in Ghana, only 62-70% of people in urban areas and 35-40% of people in the rural areas have access to treated water [20]. An undesirable consequence of the fact that Ghana has the largest gold mining industry in West Africa has been the contamination of water supplies by contaminants such as arsenic [21]. There are also many water sources in the North of the country that have high levels of fluoride, giving rise to dental and skeletal fluorosis [22].

Wind Resource in Ghana

The SWERA (Solar and Wind Energy Resource Assessment) programme began in Ghana in August 2002 as part of a global project to supply high quality renewable energy resource information [23]. The assessment of the wind resource covered the whole of Ghana with the primary focus being on the potential for large-scale grid connected wind turbines. The collection of dependable data on the wind resource in Ghana only began in 1999 when the Energy Commission started taking measurements at 11 coastal sites East and West of the Meridian (around Accra). The monthly average wind speed at 12 m is 4.8–5.5 m/s, which shows that Ghana has an adequate wind resource for power generation, as average wind speeds of greater than 4m/s are generally considered to have generation potential.

As part of the SWERA project the National Renewable Energy Laboratory (NREL, USA) developed high-resolution (1 km²) wind energy resource maps for Ghana [24]. The mapping system used by NREL is a combination of analytical, numerical and empirical methods using Geographic Information System (GIS) mapping tools. The best surface data for the wind assessment was obtained from the measurement stations along the coastline mentioned above, whilst the rest was computed from satellite ocean wind measurements. The resulting wind energy resource map shows that there is a Class 2 (6.2 – 7.1 m/s) wind resource at a height of 50 metres along the coast in southeast Ghana, around Accra [25]. There is a good to excellent Class 5 (8.4 – 9.0 m/s) wind resource in the higher regions northwest of Accra and along the border with Togo. The studies showed that the total land area with a Class 3 wind resource or higher is 1128 km², which represents about 0.5% of Ghana's total area.

In order to investigate the potential performance of the membrane system in Ghana, average monthly wind speed data was used from a previously published study [26]. The average monthly values were based on the average daily mean value at a height of 2 m above the ground from readings taken close to Accra. The log law was used in order to give the wind speeds at a height of 8 m, which is a more realistic hub height for a wind turbine mounted on top of the trailer for the membrane system. *Figure 1* shows the variation in the average monthly wind speed in Accra at a height of 8 m. The average wind speed is 4.3 m/s over a range from 3.8 – 5.4 m/s. The wind speed characteristics are better analysed using the Weibull distribution, which calculates the probability that the wind speed will exceed a certain value [27]. A Weibull shape factor of 3 was used, as this is typical of areas which experience the trade winds. The Weibull distribution for Accra (*Figure 2*) shows how the higher shape value factor means that the curve has a sharp peak, indicating less wind speed variation. In general, the average wind speed data for Accra shows an adequate wind speed velocity with little variation, which is well suited to wind energy production.

Small Wind Turbine Comparison

The Weibull distribution and wind turbine power curves were used to compare eight different wind turbines that are currently marketed in the UK. This allowed the calculation of the annual energy production of the wind turbines based on the wind data for Accra, which provides a good basis for determining the most feasible wind turbine for this particular situation. *Figure 3* shows the total annual energy production and the capacity factor for each of the eight wind turbines. The capacity factor is the ratio of energy generated over the year to the energy that the wind turbine would produce at its rated power over the same time period. The Proven Energy wind turbine has the highest capacity factor giving a good indication of how efficiently it would operate in the given wind conditions. The Swift wind turbine produces up to twice the amount of energy of some of the other designs, and initially this seemed to be an obvious result due to a higher rated output of 1.5 kW compared to power ratings of 1.1 kW or less for the other models. Further analysis of the performances of the wind turbines (*Table 2*) is required in order to make an accurate comparison.

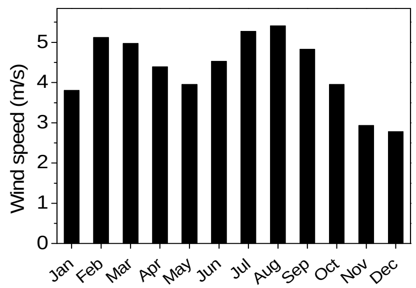

Figure 1. Mean monthly variation in wind speed (1991) [26]

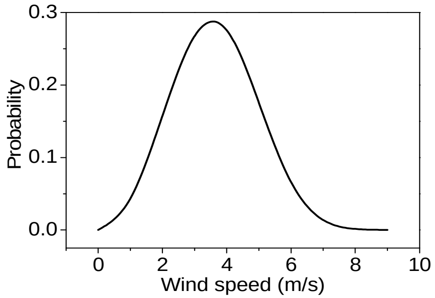

Figure 2. Weibull distribution, k=3 (Accra).

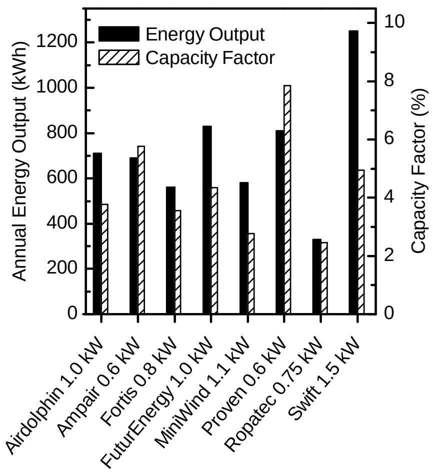

Figure 3. Comparison of calculated annual energy production and capacity factor (Accra, 1991).

The comparison of wind turbine performance shown in *Table 2* highlights the differences in their annual energy output with respect to their operating characteristics. When the wind turbine hub height is increased from 4 to 8 m, the energy output approximately doubles for each of the turbines for this particular location and conditions. At lower average wind speeds, it becomes apparent that the cut-in wind speed (when the turbine starts to generate power) and the initial steepness of the power curve have a large effect on energy output. This is highlighted by the fact that although the MiniWind wind turbine is rated at 1.1 kW, it has a high cut-in speed (3.8 m/s) and a relatively shallow power curve and therefore has a similar energy production to the Ampair 600 W wind turbine. It must be noted that this performance comparison is unique for this situation where the average annual wind speed is relatively low for wind energy production.

Table 2. Comparison of several small wind turbines available in the UK, rated at 1.5kW or less. [28]

Manufacturer	Rated Power (kW)	Rated Speed (m/s)	Cut-in Wind Speed (m/s)	Blade Diameter (m)	Generator Output (V_{DC})	Approx. Cost (£k)	Capacity Factor 4m (%)	Annual Energy Output: Accra (kWh)	
								4m	8m
Airdolphin	1.00	12.5	2.5	1.0	25	6.5	5	425	710
Ampair	0.60	11.0	3.0	1.7	48	2.9	7	389	580
Fortis	0.80	14.0	3.0	2.2	24	1.5	5	320	590
FuturEnergy	1.00	12.5	3.2	1.8	48	0.7	6	490	830
MiniWind	1.10	12.0	3.8	1.8	48	0.8	4	343	580
Proven Energy	0.60	12.0	2.5	2.6	48	2.9	10	531	810
Ropatec	0.75	14.0	2.0	1.5	48	2.8	3	207	340
Swift	1.50	12.0	2.3	2.1	240*	6.2	6	836	1250

*Voltage is V_{AC}

Discussion of Results

In order to get some indication of the predicted performance of the membrane system coupled to a wind turbine, the quantity of fresh water that can be produced is a simple calculation. For this purpose, a SEC of 1.8 kWh/m³ is used which is representative of a BW30 membrane operating with brackish feed water (TDS 8290 μS/cm) at 11 bar and 400 L/h [4]. Using this SEC and the annual power output of the FuturEnergy 1kW wind turbine operating in Accra, the membrane system could theoretically produce about 1.3 m³/day (assuming all of the produced energy could be used and the specific energy consumption did not vary significantly). This would be a sufficient supply of clean water to provide a small community of about 50-100 people. When comparing the wind turbines that were analysed the Proven Energy wind turbine appeared to have the best overall performance, but when cost is taken into consideration it quickly becomes apparent that the 1kW FuturEnergy wind turbine is the most economical and efficient wind turbine for this specific application. Further analysis of detailed wind data and the performance characteristics of the membrane filtration system through pilot tests are required before an accurate judgment of the system performance in this particular location can be made.

Conclusions

There is a need for further research into the area of brackish water desalination by small scale wind-powered membrane systems. Most of the research done in this area has been directed at larger scale systems (for example Enercon systems, which produce >175 m³/day [29]) and does not have the same implications on a smaller scale. The results of these wind turbine analyses show that a wind-powered membrane system would provide a sufficient quantity and quality of water, depending on the average wind speed. For this particular system, initial research shows that an average wind speed of >4 m/s seems to be adequate. Testing of the prototype membrane system is required to investigate the effects of transient operation on the permeate flow rate and purity, especially considering the variability of an energy source like the wind.

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